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# NEW DEVELOPMENTS AND OPPORTUNITIES IN 3D PRINTING

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## Executive Statement

In recent years, several factors have allowed a number of new methods for small-scale manufacturing in plastic, metal and ceramic to become widespread . These techniques are potentially very useful in many types of devices and products, especially in terms of their design and implementation. This paper explores why and how this technology has recently become so ubiquitous and how it can be of benefit to scientists, engineers and consumers across many different sectors.

Previously known as additive manufacturing or rapid prototyping, but now generally termed 3D printing, these groups of technologies and methods utilise bottom-up fabrication: building up exact parts in a stepwise fashion from extremely small pieces. This is in contrast to traditional top-down subtractive techniques, whereby a large block of starting material is reduced to a smaller part or mould via machining or ablation, and formative techniques, such as injection moulding, where the material is heated to beyond its melting point and then poured to set inside a mould. The vast majority of manufactured parts are currently produced by either subtractive or formative techniques. The former is favoured for precision parts due to its accuracy and the latter for mass production owing to its speed per object. However, computer-numerical-control (CNC) milling machines used in subtractive manufacturing are complicated, costly and wasteful, as much of the material is chipped away and discarded, whilst formative manufacturing requires an accurate prototype for mould-casting, and the handling of large quantities of molten material.  As a result product manufacturing has remained, for the most part, the domain of specialists, and large costs and waiting periods are often an obstacle to rapid physical production.

Through 3D printing, however, mock-ups and prototypes can be made and remade in small volumes, massively reducing cost and time barriers to use of product or even to market. The desired object is designed using CAD software (generally output as a .stl file) and then computationally sliced into layers. Algorithms determine the most topologically efficient path to take, are used to fill to make, and support material to generate, each layer in order, to give the finished item desired properties such as finish or strength using the least material in the shortest time.

Technological, social and legal factors have come together to create the current explosion in the use and development of 3D printing techniques. The ubiquity of connected, powerful computing has lowered the barrier to entry of CAD and 3D printer file generation and enabled widespread sharing and customisation of designs, accelerated by the socioeconomic changes associated with the internet. Accurate stepper motors, precision-machined metal parts and IC control boards continue to become cheaper, whilst open-source software has rendered the underlying theory and implementation accessible to all.

A number of patents covering 3D printing expired recently (in the case of plastics printing), or are due to expire in 2014 (in the case of metal and ceramics), enabling a grassroots movement of open sourced collaborative kit building and development in hardware, software and firmware. Such kit-based approaches are potentially as disruptive as high throughput high accuracy multi-material industrial machines, for they skirt a number of current legal unknowns and also lend themselves to easy modification, resulting in the rapid evolution of machines and methods.

## Contents

## 1. Aims of this document

The aim of this report is to outline and examine the established and emerging trends and technologies in 3D printing (or additive manufacturing) of plastics, metals, ceramics, composite and biological materials, as well as its impacts on areas such as rapid prototyping, product design, biotechnology, food technology, established industries with large scale traditional manufacturing, and intellectual property. This document focuses on the challenges and obstacles that this relatively new technology must overcome to continue advancement and impacts in a wide range of sectors.

## 2. Introduction

3D printing technology can be broadly divided up into four non-proprietary methods - Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), and Direct Laser Deposition (DLD) - and four other proprietary methods - three Dimensional Printing (3DP), Polyjet Matrix Printing, Electronic Beam Melting (EBM), and Laminated Object Manufacturing (LOM).

**Stereolithography (SLA)**
SLA is the oldest 3D printing technology, and was commercialised by 3D Systems in 1986. It involves the use of a liquid bath of photopolymer, which is polymerised in a stepwise fashion either by optics such as DLP (digital light processors) or UV laser on a vertically moving print-bed. After printing it is washed and further cured in an oven. Support material, in this case a thin, easily removable part of the same polymer, is used to support overhanging structures. In 2013 the MIT spinout Formlabs raised nearly $3m through crowdfunding platform Kickstarter to commercialise an affordable SLA machine; the company was sued heavily by 3D systems (more on this in "Potential barriers and threats", below).

**Selective Laser Sintering (SLS)**
SLS is conceptually similar to SLA but uses metal or ceramic powders instead of liquid photopolymer, with a gradually descending print bed and a much more powerful laser to fuse the powder together incrementally. The bed is lowered once a layer has completed, and a wiper used to redistribute the powder as the object is built up. Again, further cleaning, removal of support material and annealing is required.

**Direct Laser Deposition (DLD)**
Also called laser-deposition technology, laser metal deposition and metal deposition technology. This class of machine forms objects by blowing powdered feedstock, usually metal, through a melt pool where multiple laser beams are focussed, causing the molten

powder to coalesce into a larger unit. This method is still somewhat experimental, but is already utilised by large engineering firms including EASA, and seems promising for high-end production due to the prospect of multi-axial control (the print-head is able to pitch, roll and yaw, eliminating the z-axis layer constraints imposed through other methods), and multi-metal printing, both of which are unobtainable through SLS. Issues arise in the regulation of powder consistency and the accidental melting of residual powder.

**Three Dimensional Printing (3DP)**
3DP was invented in 1993 and subsequently developed and commercialised by Z Corporation. It uses a powder which is glued together by a binder deposited by a moving head; as with SLS, the build platform is lowered and a wiper is used to redistribute the powder evenly. The unbound powder acts as a support but parts are very fragile and must be cleaned and cured carefully. Colorants can also be selectively added to the liquid binder to fabricate multi-coloured parts with high resolution.

**Polyjet Matrix Printing**
This process, developed exclusively by Objet, uses fine jets or droplets of liquid polymer to build up parts which are UV polymerised upon deposition. The print head can generate multiple droplets at the same time, including a variety of colours and water-soluble support material than can easily be washed away after printing.

**Electronic Beam Melting (EBM)**
Developed by Arcam in the late 90s, this process fuses metal powder on a build platform using an electron beam, permitting a finer resolution than the similar SLS method and negating the need for post-production heat treatment. However, the build chamber is evacuated and maintained at temperatures of around 700-1000°C.

**Laminated Object Manufacturing (LOM)**
Developed by Helisys, this technology cuts sheets of thin material by knife or laser, and glues them together in a stepwise fashion. Excess material is broken off, leaving the final object. LOM mainly uses paper but plastics are also possible.

**Fused Deposition Modelling (FDM)**
FDM was developed in the late ‘80s and commercialised by Stratasys in the early ‘90s. A material, usually a thermo- or duro-plastic, is heated and extruded through a small nozzle moved accurately through the x, y and z axes (alternately the print bed can move along one axis instead to reduce mechanical complexity). The material is deposited onto the print bed and, as it cools, it forms the basis for the next layer. For some plastics (notably ABS) the coefficient of thermal expansion is such that the print bed is heated or enclosed to ensure rapid cooling to room temperature does not reduce adhesion of the part to the print bed or cause part delamination (de-bonding of concurrently printed layers due to shrinking).

Resolution is limited by the nozzle's orifice diameter, which is typically 0.1-0.5mm, but can be much smaller, depending on the properties (such as viscosity) of the material being printed. FDM is currently the main method of open source printing (embodied by the RepRap project which produces open-source 3D printers capable of cloning most of their non-generic components). Many such hobby kits have been sold, usually with their plastic parts having themselves been printed. The RepRap inspired MakerBot product line has been very successful in making 3D printing accessible to home users, and was acquired by Stratasys for $403 million in 2013.

All the techniques described here have disadvantages and advantages in terms of technical specifications such as resolution, modification potential for research and development, material restrictions, etc. FDM is presently the most widespread technique as cheap kits can be built for a few hundred pounds, offering around 100µm scale accuracy in a number of thermo- and duro-plastics.

FDM printing is overwhelmingly open sourced, with printers and kits available now containing many design iterations of incremental improvements in cost, resolution and reliability. RepRap printers maintain a strong market share of around 20% against much larger companies.

It is also worth noting that a number of SLA and SLS based patents are due to run out during the course of 2014 or have already done so.

## 3. Applications, state of the art approaches and breakthrough areas

The 3D printing economy can be divided broadly into the high-end market, low-end market and the experimental community. The low-end market comprises hobbyists and inventors/designers, where products are created for personal use using FDM (usually RepRap or Makerbot) or SLA. The science community also benefits from being able to rapidly and inexpensively produce customised plastic laboratory equipment. The low-cost printers arising from this market are now being disseminated across the developing world for production of patient-specific prostheses.

The high-end market uses SLS, EBM and DLD machines to produce durable metal parts of very high quality. Airbus, for example, used 3D printing to produce an engine cover hinge with comparable mechanical strength yet half the weight of previous design iterations. This optimised design would not have been possible without powerful computational techniques and 3D printing. Similarly EADS used EBM to produce a titanium mast node that has been orbiting the Earth as a component of Atlantic Bird 7 since 2011. The technology is very well suited for such low-volume production runs, and the European Space Agency (ESA) AMAZE project aims to optimise 3D printing of metals so that a machine may be placed aboard the International Space Station.

The experimental community comprises academics and technology companies investigating innovative means of producing higher-quality prints, as well as expanding the catalogue of printable materials and the production of complex or biological items. Some of the more interesting developments are reviewed below.

**Printing glass**

SLA photopolymer products are inherently translucent until cured in an oven, but are very fragile in their uncured state. A team from Washington State University have created a process dubbed" vitraglyphics" for printing with glass, whereby finely powdered silicon-dioxide is affixed with a binding resin, as in 3DP, and then cured. However, vitraglyphic prints are not transparent. More promisingly, Printoptical Technology from Dutch company LUXeXceL uses Objet style polyjet matrix technology with piezoelectric control to release miniscule drops of liquid which are then cured by UV light, following a small delay allowing the fluid to flow. Though not technically glass, the method is capable of producing optics-grade lenses for research and spectacles without the need for post-processing, and was named in the 2012 Wohlers Report (the most comprehensive and highly regarded annual 3D printing review) as one of five key emerging technologies that will change the additive manufacturing landscape. Another interesting product in this area is the Solar Sinter by Markus Kayser. Designed to be used in the desert, the machine harnesses solar energy to melt sand into non-transparent glass.

**Printing electronics**

Printed circuit boards (PCBs) have long been fabricated through a number of techniques, most of which fall in line with subtractive manufacturing. Typically, a layer of copper is attached to a non-conductive substrate, and the unwanted copper is then etched or dissolved away, leaving the required connections on the board. However, such methods may also be implemented in a modified 3D printer as they share the 3-axis architecture. Printing a circuit board purely through additive processes would be challenging due to the large temperature differences between conductors and insulators, though there is research underway to resolve this.

Much ongoing research surrounds the printing of circuit components. The aforementioned LUXeXceL specialises in printing LEDs with Printoptics, and many publications exist on producing thin-film transistors using inkjet methods. Researchers from MIT and the Universities of Oxford, Cambridge and Sheffield have developed means of spraying polymeric photovoltaics onto flexible surfaces and glass using chemical vapour deposition, loosely considered to be a form of additive manufacturing.

A Harvard University research team recently printed $1mm^3$ lithium-ion batteries by extruding two micrometre-scale interwoven combs (the anode and cathode) of lithium metal oxide paste and immersing in electrolyte. The prints were produced using FDM with a micro-scale orifice, where the miniscule extrusions were permitted due to the specific fluid properties of the paste used. The batteries boasted performance comparable with their traditionally manufactured counterparts.

In 2013, a group from Cornell University printed all the components for a fully functioning loudspeaker, albeit on multiple printers, with the pieces requiring assembly afterwards. The cone and frame were printed in plastic using FDM, whilst the coil and wiring were produced using silver ink. The magnet was printed using an extrudable strontium-ferrite based material.

**Printing food**

Much attention from the maker movement has been devoted to using modified RepRap machines to print objects made from chocolate. The food, with a melting point of 17-36°C, lends itself well to heat-extrusion methods and permits chocolatiers to experiment with previously impossible aesthetics. Similarly, California design firm The Sugar Lab worked with 3D Systems to produce ChefJet, a 3DP-style machine that selectively binds powdered sugar in layers using alcohol to produce elaborate edible sculptures.

NASA have recently commissioned an ambitious investigation into whether food could be 3D printed in space. Currently food available to astronauts must be prepared entirely on Earth and sealed until the moment of consumption, and does not meet the nutritional requirements, 5-year shelf life and psychological variety that would be necessary for a Mars mission. The investigators hope to develop a machine utilising sealed cartridges of ingredients from which numerous meals could be produced through 3D printing. If successful, the technology would undoubtedly find applications on Earth as well as in the rapidly expanding space industry.

In 2013 the world’s first in vitro hamburger was presented to food critics; it  was produced by encouraging muscular stem cells taken from a cow to grow and merge into thin strips, which were then shaped into a burger. There has been much debate about whether this will eventually become the norm as both the world’s population and its demand for protein increases. Compared with the equivalent figures for genuine meat, the lab-grown burger produced 4% of the greenhouse emissions and required only 1% of the land use. However, it used only 46% less energy in total. We speculate that techniques used for printing biological matter, covered in the next section, could be employed to increase energy efficiency and aid production of synthetic meat.

**Bioprinting**

Scarcity of organ donors and the possibility of transplant rejection by the recipient's immune system are still major threats to global human longevity, but are beginning to be nullified through the field of regenerative medicine, wherein the highly patient-specific macro-structure may often be obtained through 3D printing. In a landmark operation in 2011, a global collaboration of researchers used CT scans of a cancer patient's damaged trachea to create a digital 3D model, which was then reconstructed before being printed in ceramics and coated in a nanoporous composite. The printed scaffold was then seeded with stem cells taken from the patient's bone marrow before being placed in a bioreactor, where the cells were able to take hold inside the nanopores and develop into tracheal cells. The resulting artificial windpipe was then successfully implanted into the patient, who survived.

Modified FDM printers can be made to extrude hydrogels and as such have found widespread use in printing substrates for biological matter. In 2013 a Princeton University research group merged techniques for printing electronics and living tissue to produce a functional bionic ear with hearing capabilities well outside those of the standard human frequency range. The hydrogel was seeded with calf-cells, which later hardened into cartilage, whilst the antennae and coil were formed by selectively embedding silver nanoparticles into the hydrogel matrix. The group stated that the end of the conductive coil could then be connected to a patient's nerve endings to potentially restore hearing.

Researchers at Heriot-Watt University have also modified an FDM printer to print 3D structures composed from human embryonic stem-cells. High accuracy gentle deposition was obtained by releasing the gels with microvalves, allowing the cells to maintain pluripotency – the ability to differentiate into any other cell type. This holds huge promise for tissue engineering and potentially the printing of entire complex organs.

The field of orthopaedic surgery is also seeing enhancements through 3D printing. Scans of fractured anatomy are 3D printed and used by surgeons to rehearse specific operations, yielding a greater success rate for delicate procedures, and some patient-specific implants are now themselves printed. For example, surgeons at the University of Hasselt, Belgium produced a replacement lower jaw from titanium using SLS. The print was then coated in bio-compatible ceramics, themselves printed, to aid acceptance before being successfully implanted into the 83 year old patient.  The combination of multiple printers and materials led to a composite product with a range of desirable properties.

Finally, 3D printing is also offering solutions in the pharmaceutical sector. With the development of individualised medicine for complex conditions such as HIV, patients often have to consume vast quantities of different pills throughout the day. A group at the University of Glasgow have developed a modified FDM printer capable of enacting specific chemical reactions within a printed gel substrate. This technology could lead to machines capable of producing specialised drugs on an individual basis.

## 4. Potential barriers and threats

**Legality**

The majority of the breakthroughs discussed in the previous section were based on FDM technology. This is partially because FDM, whilst often lacking in speed, resolution and strength, is the technique best suited for adapting to novel materials. It is also largely due to the fact the key patent covering FDM expired in 2009, allowing for a severe price reduction in such machines and subsequent mass uptake and experimentation. Clearly patent expiry is a strong catalyst for innovation in this field, however would-be innovators are still beset with difficulties as numerous improvements, often essential, are covered by additional patents that may not have expired.

This was highlighted in 2012 when 3D Systems launched a lengthy lawsuit against the startup Formlabs, claiming that the latter's Form1 stereolithography device infringed Patent US5597520 A, "Simultaneous multiple layer curing in stereolithography". Whilst the fundamental patents covering SLA expired in the early 2000s, the complex IP landscape has prevented inventors from taking risks for fear of accidentally becoming involved in a legal battle. A settlement was reached for the patent (which itself expired in January 2014) and Formlabs' low-cost, high-quality SLA machine is now on sale.

On 28 January 2014 the key patent covering SLS printing expired, potentially leading to affordable metal-capable devices. Although this will have some impact on the open source community, the much higher technical requirements of motor and temperature control involved in micron-accurate laser sintering of ceramics and metal or UV laser polymerisation will keep costs relatively high. However, low volume prototyping services may arise offering significant cost benefits over traditional techniques. The much lower speed of manufacture and the increased internal stresses in SLS-formed metal or ceramic parts make this technology unlikely to impact on high volume manufacture of conventional items in the near term. However, unexpected innovations may overcome these challenges and change that outlook.

**Quality/economics**

For decades, 3D printing has been excellent for rapid prototyping of individual objects, and the emerging techniques reviewed here may empower individuals to create complex mechanical, electronic and biological devices. The process is, though, still orders of magnitude slower than traditional methods of mass production and is unlikely to be able to compete with them any time soon. However, our changing relationship with consumer products could well expand the niche market currently in place for 3D printing customised jewellery and other accessories into a wider field of more advanced goods.

In addition to its reduced speed, the quality of 3D printed parts is not usually on par with those made through formative methods, largely due to weaknesses along the transplanar axis and the variable consistency of sintered powder. Repeatability is also an issue, with variability between 3D printed parts - even those produced from the same instructions on the same machine - often being too high for end-user products. The ESA's AMAZE project aims to remedy these shortfalls through  research focussed on increasing the quality of printed metal so that it can be a viable production means for even the most precise parts.

Standardisation may also be a barrier. Prior to the current patent cliff, 3D printing was controlled by a handful of companies, each with a dedicated client base and its own set of standards. No clear or defined standards for printers and their output exist for machines currently on the market, , though this is changing gradually due to the dynamic nature of the new industry.

A 2013 report commissioned by IBM highlighted that economics of scale do not apply to 3D printing yet but suggested that the practice, when used in conjunction with the other emerging technologies of intelligent robotics and open-source architecture, is still likely to catalyse disruptive transformation to the manufacturing ecosystem.  Extrapolating current trends in these three fields and using four common consumer goods, the report forecast that by 2022 the products will be, on average, 23% cheaper and require 90% less volume than in traditional means when manufactured using 3D printing, automated intelligent robotics and open-source architecture. However, despite shrinking and localising the global supply chain, the model predicted that this new approach to fabrication will not necessarily be more eco-friendly. Although the report used the term "on-demand manufacturing", the authors did not make predictions about the time required to produce complex consumables.

**Sustainability**

Whilst touted as being more environmentally friendly than subtractive manufacturing due to reduced swarf (waste), 3D printing is still far from eco-friendly. Surplus material is generated through the support structures (required for most methods, depending on what is being printed) and failed prints. High-end commercial printers have a typical success rate of  ~90%, and this value is often far lower for cheaper models. The two thermoplastics typically used in FDM printers are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). Unlike ABS, PLA is corn-starch derived, biodegradable and can be recycled under SPI Resin Identification Code 7. However, it has less desirable thermal properties, becoming soft at around 50°C, and ABS is still often the material of choice in the FDM community, especially those making electrical, mechanical or kitchenware products. Research into heat-resistant PLA is currently an active field, and machines such as the Filastruder exist to recycle old ABS (from plastic bottles, etc.) into filament suitable for printing.

## 5. Parameters for challenges and prizes

- Higher quality output and reproducibility between printers of the same and differing models and even techniques.
- Minimisation of cost and complexity of printer dissemination globally, particularly in the developing world.
- Static and dynamic mechanical strength of printed parts (composites, prosthetics, building materials).
- Maximising computational efficiency of design software and firmware – pathing, support material generation, filling and packing algorithms in order to increase productivity as well as lowering cost barriers to entry.
- Print speed and scale maximisation without commensurate increases in error and failure rates.
- Viability of printed organs or organelles in vivo or in vitro, for either medicine or cuisine.
- Printing of complex composites for sensing, electronics, smart materials and surfaces, exoskeletons and prosthetics.
- Consolidating multiple emerging techniques for producing advanced components into a single machine.
- Sub £1000 open source desktop SLS printer (using expired patents).

## 6. Author biographies

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Mark Ransley is a student on UCL's CoMPLEX doctoral training programme and also works on the Wearable Assistive Materials project.

## 7. Acronyms

3DP: three dimensional printing

ABS: acrylonitrile butadiene styrene

CAD: computer aided design

CNC: computer-numerical-control

DLD: direct laser deposition

DLP: digital light processor

EBM: electronic beam melting

ESA: European Space Agency

FDM: fused deposition modelling

IC: integrated circuit

IP: intellectual property

LED: light emitting diode

LOM: laminated object manufacturing

MIT: Massachusetts Institute of Technology

PCB: printed circuit board

PLA: polylactic acid

SLA: stereolithography

SLS: selective laser sintering

UV: ultraviolet

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